WIYN Open Cluster Study. X. The K-Band Magnitude of the Red Clump as a Distance Indicator

Aaron J. Grocholski and Ata Sarajedini

Department of Astronomy, University of Florida, P. O. Box 112055, Gainesville, FL 32611
aaron@astro.ufl.edu, ata@astro.ufl.edu

ABSTRACT

In an effort to improve the utility of the helium burning red clump luminosity as a distance indicator, we explore the sensitivity of the K-band red clump absolute magnitude [$M_K(RC)$] to metallicity and age. We rely upon JK photometry for 14 open clusters and two globulars from the 2nd Incremental Data Release of the 2MASS Point Source Catalog. The distances, metallicities, and ages of the open clusters are all on an internally consistent system, while the K(RC) values are measured from the 2MASS data. For clusters younger than ∼2 Gyr, $M_K(RC)$ is insensitive to metallicity but shows a dependence on age. In contrast, for clusters older than ∼2 Gyr, $M_K(RC)$ is influenced primarily by the metallicity of the population and shows little or no dependence on the age. Theoretical red clump models based on the formalism of Girardi et al. reinforce this finding. Over comparable metallicity and age ranges, our average $M_K(RC)$ value is in accord with that based on solar-neighborhood red clump stars with HIPPARCOS parallaxes. Lastly, we compute the distance to the open cluster NGC 2158 using our red clump calibration. Adopting an age of 1.6 ± 0.2 Gyr and $[Fe/H] = -0.24 \pm 0.06$, our calibration yields a distance of $(m - M)_V = 14.38 \pm 0.09$.

Subject headings: open clusters and associations: general – stars: color-magnitude diagrams – stars: distances – stars: horizontal branch

1. Introduction

During the past few years, the helium burning red clump (RC) has gained considerable attention for its potential as a standard candle. The primary advantage of the RC is the ease with which it can be recognized in the color-magnitude diagram. However, there is currently a great deal of controversy in the literature regarding the appropriate treatment of possible metallicity and age effects on the I-band absolute magnitude of the RC ($M_I(RC)$). There are two schools of thought on this issue; the first assumes a constant value for $M_I(RC)$ which is then used to facilitate a single-step distance determination via knowledge of the apparent RC magnitude and the extinction (e.g. Paczyński & Stanek 1998; Stanek & Garnavich 1998). The second approach is founded on the claim that both age and metal abundance have a significant influence on the luminosity of RC

stars (e.g. Cole 1998; Sarajedini 1999) and must be accounted for in determining $M_I(RC)$ and therefore the distance.

Both Paczyński & Stanek (1998) and Stanek & Garnavich (1998) use HIPPARCOS RC stars with parallax errors of less than 10% to calculate the I-band absolute magnitude of the solar neighborhood red clump. In their analysis, Paczyński & Stanek (1998) find that $M_I(RC)$ shows no variation with color over the range $0.8 < (V - I)_0 < 1.4$ and, from a Gaussian fit to the RC luminosity function, find $M_I(RC) = -0.28 \pm 0.09$. Following the same methodology and building upon the earlier work, Stanek & Garnavich (1998) find a similar result with $M_I(RC) = -0.23 \pm 0.03$. With this calibration, a single step calculation is then used to determine the distance to the Galactic center (Paczyński & Stanek 1998) and M31 (Stanek & Garnavich 1998). Both of these investigations found little or no variation in M_I of the RC stars with color; this was taken to imply that $M_I(RC)$ does not vary significantly with metallicity.

In contrast, theoretical models from Girardi & Salaris (2001) and the earlier models of Seidel, Demarque, & Weinberg (1987; see also Cole 1998) show that $M_I(RC)$ is dependent on both age and metallicity, becoming fainter as both increase. These models are in good agreement with the observations presented by Sarajedini (1999, hereafter S99). Using published photometry for 8 open clusters, S99's most important result is that while $M_I(RC)$ is less sensitive to metal abundance than $M_V(RC)$, both still retain a considerable dependence on the age and metallicity of the stellar population. As a result, the single-step method of applying the solar-neighborhood $M_I(RC)$ to populations with a different age-metallicity mix could be problematic.

Alves (2000) also uses the HIPPARCOS RC for his calibration; however, he relies upon the K-band luminosity (M_K) of the RC stars in the hope that, since the K-band is less sensitive to extinction (and possibly metallicity as well) than the I-band, it might make a better choice as a standard candle. Alves (2000) restricts his RC stars to those that have metallicities from high resolution spectroscopic data. For this group of 238 RC stars, he finds a peak value of $M_K(RC) = -1.61 \pm 0.03$ with no correlation between $[Fe/H]$ and M_K. However, he is not able to explore the effect of age on $M_K(RC)$ due to the lack of such information for the individual stars in his sample.

These previous works have prompted us to combine the approaches of S99 and Alves (2000) and to investigate the influence of age and metal abundance on $M_K(RC)$ for a number of open clusters with well-known distances and metallicities. In section 2 we discuss the observational data. Section 3 compares our data with the results of theoretical models and presents a discussion of the results; our conclusions are summarized in Section 4.

2. The Data

2.1. Open Clusters

In the present study, the most important criterion that the observational data must fulfill is that of internal consistency. For example, we must ensure that the distance moduli, reddenings, ages, and metallicities of all of the clusters in our sample have been determined using the same techniques. In addition, it is imperative that the IR photometry we rely upon be measured and calibrated in a consistent manner. For the former, we use the database of open cluster properties as measured by Twarog et al. (1997), supplemented by cluster ages from the WEBDA[1] database, and, for the latter, we utilize the 2nd Incremental Data Release of the 2MASS Point Source Catalog[2]. We now discuss each of these in more detail.

Twarog et al. (1997) have compiled a list of 76 open clusters for which they provide reddenings, distance moduli and metallicities. For the purposes of the present paper, we limit ourselves to distance moduli derived via the technique of main sequence fitting so as to remain independent of methods that rely on the luminosity of the RC. Their metallicities have all been measured on the same system and the reddenings have been determined using an internally consistent method. The vast majority of these values are consistent with those found in the literature, except for the reddening of NGC 6819 for which the Twarog et al. (1997) value is much higher than other published values. As a result, we have decided to adopt the S99 reddening for NGC 6819 instead of the apparently discrepant value tabulated by Twarog et al. (1997). Additionally, because the determination of the reddening and distance modulus are coupled, we also adopt the S99 distance modulus for NGC 6819.

The ages of the open clusters have been obtained from WEBDA, which is a compilation of open cluster data from various sources. To check the reliability of the WEBDA ages, we compare them with the cluster ages determined by S99 in Fig. 1. S99 presents isochrone-fitting ages for 8 open clusters that have been determined in the same manner using the Bertelli et al. (1994) theoretical isochrones. The left panel of Fig. 1 plots the ages from S99 versus the ages in WEBDA, where both axes are in log space and the dashed line represents a zero age difference between the systems. From this plot, it is evident that there is a systematic offset between the two systems with the WEBDA ages being younger than those of S99. The average difference, $\Delta log(Age) = 0.191$, is used to shift the ages given in WEBDA onto the S99 system. The right panel of Fig. 1 shows the ages from S99 plotted against the shifted WEBDA ages; it is clear from Fig. 1 that the shifted ages are in better agreement with those of S99; as a result, we will apply this shift to nine of the clusters in our study and use the S99 ages for the five clusters that are common to both studies.

For the open clusters in the Twarog et al. (1997) study that possess main sequence fitting

[1]http://obswww.unige.ch/webda/webda.html

[2]http://irsa.ipac.caltech.edu/

distances, we extracted JHK photometry from the 2nd Incremental Data Release of the 2MASS Point Source Catalog. As noted above, these data have been obtained using similar instruments and reduced with the same pipeline techniques. For each cluster, we have utilized the same criteria for the 2MASS data retrieval. The field size is originally set to 30 arcmin in radius and then reduced to fields as small as 5 arcmin in radius in an attempt to isolate the cluster stars. The sources are limited to a brightness of 6th magnitude or fainter due to saturation effects at the bright end (Carpenter 2000). Lastly, we have extracted only the highest quality photometry from the 2MASS catalog, which provides a read flag (rd_flg) indicating how the photometry of each star was measured. We have chosen to exclude any source that has a read flag of zero in any band since this implies that the source was not detected in that band and the magnitude given is an upper limit. We note that the vast majority of the stellar magnitudes used in this study are based on point-spread-function fitting (i.e. rd_flg = 2); however, in order to include the brighter red clumps of more nearby clusters, we have had to use the aperture photometry in a minority of cases.

The 2MASS program uses a K-short (K_S) filter for their observations. We have chosen to convert these magnitudes to the K-band adopting the Bessell & Brett (1988, hereafter BB) system, which is also used in the theoretical models of Girardi et al. (2000) and Girardi & Salaris (2001). The transformation equations are derived by Carpenter (2001) and are adopted as follows:

$$(J - K_{BB}) = [(J - K_S) - (-0.011 \pm 0.005)]/(0.972 \pm 0.006) \tag{1}$$

and

$$K_{BB} = [K_S - (-0.044 \pm 0.003)] - (0.000 \pm 0.005) * (J - K_{BB}). \tag{2}$$

We note, however, that transformation to the Koornneef (1983) K-band (used by Alves 2000, Sec. 3.2) would have a negligible effect on our results. To correct for the interstellar reddening, we adopt the extinction law determined by Cardelli et al. (1989), which, using their value of $R_V = 3.1$, gives $A_K = 0.11A_V$ and $A_J = 0.28A_V$. From this, it is a simple matter to calculate the absolute K-band magnitude and dereddened $J - K$ color of the open cluster stars.

We have determined the RC luminosity for our clusters by taking the median value of M_K for all stars within a standard sized box placed around the RC. We use the median value of M_K along with a constant box size in an attempt to eliminate any selection effects that may occur in choosing the location of the RC and to limit the effect of outliers on $M_K(RC)$. Figure 2 shows the color-magnitude diagrams (CMDs) for all 14 clusters focused on the RC and main sequence turnoff. The box used to select the RC stars for each cluster is also shown. We note that, where available, we have used published optical CMDs for our clusters to help isolate the approximate RC location. The uncertainty in $M_K(RC)$ is calculated by combining the standard error about the mean K-magnitude for all stars inside the red clump boxes along with the errors in $E(B-V)$ and $(m-M)_V$, all added in quadrature. Except where otherwise noted, we adopt 20% of the value as the error in $E(B-V)$ and 10% of the value as the error in $(m-M)_V$.

2.2. Globular Clusters

It is difficult to ensure that the distances, ages, and metallicities of globular clusters with RCs are on the same system as those of the open clusters. Fortunately, the ages and metallicities of the two globulars in our sample - 47 Tuc and NGC 362 - are sufficiently different from the bulk of the open clusters that small systematic discrepancies in these quantities should not be a significant hindrance to the interpretation of the results. In any case, we have decided to adopt literature values for the basic cluster parameters and use the globular cluster RCs as a consistency check.

In the case of 47 Tuc, we adopt the metallicity quoted by Carretta & Gratton (1997) of $[Fe/H] = -0.70 \pm 0.07$, which happens to be very close to the Zinn & West (1984) value. For the distance modulus and reddening, we average the published values listed in Table 2 of Zoccali et al. (2001) to obtain $(m - M)_V = 13.45 \pm 0.21$ and $E(B - V) = 0.044 \pm 0.008$, where the errors represent half of the range of tabulated values. Lastly, for the age of 47 Tuc, we adopt the oldest age for which the models predict the presence of a red clump at its metallicity - 12 Gyr.

For NGC 362, we adopt a similar approach. The metal abundance of $[Fe/H] = -1.15 \pm 0.06$ is taken from Carretta & Gratton (1997), which is approximately 0.1 dex more metal-rich than the Zinn & West (1984) value. Our search of the literature has revealed distance moduli that range from $(m - M)_V = 14.49$ (Zinn 1985) to 14.95 (Burki & Meylan 1986; see also Bolte 1987) and reddenings in the range $E(B - V) = 0.032$ (Vandenberg 2000) to 0.08 (Alcaino 1976) leading to adopted values of 14.70 ± 0.23 and 0.048 ± 0.024 for the apparent distance modulus and reddening of NGC 362, respectively. Once again, we adopt an age of 12 Gyr.

The red clumps of these globulars have been isolated in the 2MASS point source catalog in the same way as for the open clusters. The $(M_K, (J - K)_0)$ CMDs for 47 Tuc and NGC 362 are shown in Fig. 3 along with the box used to define their RCs. All of the relevant observational parameters for the open and globular clusters are listed in Table 1.

3. Results and Discussion

3.1. Cluster Data

As described in Sec. 1, we are interested in exploring the dependence of $M_K(RC)$ on $[Fe/H]$ and age. Plotted in Fig. 4 are the $M_K(RC)$ values for the 14 open clusters (open circles) and the two globulars (filled circles) in our sample versus the logarithm of the age (top right panel) and the metallicity (top left panel). The red clumps start out very bright at young ages and decrease in brightness by almost one magnitude as the cluster ages approach 10^9 years after which they brighten by ~ 0.5 magnitude. Then, the red clumps become slightly fainter as the cluster ages increase up to 10^{10} years. The top two panels of Figure 4 also include $M_I(RC)$ (open squares) from S99. Keeping in mind that the numbers of clusters is small, over the age and metallicity range common to both studies, the K-band absolute magnitude of the RC exhibits less sensitivity to age

and metal abundance than does $M_I(RC)$.

3.2. Field Star Data

Alves (2000) reports K-band absolute magnitudes of solar-neighborhood stars in the HIPPARCOS catalog along with parallaxes and proper motions. Following the analysis of Alves (2000), we have limited ourselves to stars with $2.2 < (V-K)_0 < 2.5$ and $-2.5 < M_K < -0.8$ in Table 1 of Alves' paper in order to isolate a sample of nearby red clump stars. We have plotted M_K vs $[Fe/H]$ for these stars in the bottom panel of Figure 4 (open circles). For comparison, the open and globular cluster data from the present work (filled circles) are also shown. Keeping in mind that there are far fewer open clusters than field stars in Fig. 4, we find good consistency in the locations of the two samples. Alves (2000) finds $\langle M_K(RC)\rangle = -1.61 \pm 0.03$, while the open clusters in our sample give $\langle M_K(RC)\rangle = -1.62 \pm 0.06$. This is remarkable given the fact that the open cluster distances are based on the main sequence fitting results of Twarog et al. (1997) and the field stars are on the HIPPARCOS distance scale. Both show mean K-band magnitudes of ∼–1.6 and very little if any dependence on metal abundance over the same range.

3.3. Comparison With Theoretical Models

Leo Girardi has kindly provided us with theoretical models that represent the median magnitude of the red clump as a function of age and metal abundance (Girardi & Salaris 2001; Crowl et al. 2001). Figures 5 and 6 show these theoretical models in the K-band compared with our open and globular cluster data. The nine panels of Fig. 5 display the K-band luminosity of the red clump as a function of metallicity for a range of ages. The five panels in Fig. 6 illustrate the variation of the K-band luminosity with age for a range of metal abundances. In both of these figures, clusters that are similar in metallicity or age to the model plotted in each panel are represented by filled circles while the remaining clusters are denoted by open circles. Figures 5 and 6 suggest that at ages younger than ∼2 Gyr, the red clump luminosity is greatly dependent on the age of the cluster and shows little effect from the metallicity whereas clusters older than ∼2 Gyr show the exact opposite, having little age dependence while still showing the effects of metallicity.

To facilitate a more detailed comparison between the models and the observations, we utilize an interpolation routine based on low order polynomials to compare the theoretical M_K values with the observed ones. As a test of the interpolation, we have applied it to the observational data alone comparing the interpolated $M_K(RC)$ values to the actual values at the age and abundance of each cluster. We find that the root-mean-square of the residuals is negligible in $M_K(RC)$ with no systematic trends as a function of age or abundance. We have also tested the interpolation routine on the theoretical models with similar encouraging results. The accuracy of the interpolation allows us to compare the $M_K(RC)$ values predicted by the models for a given age and metallicity to the

observed $M_K(RC)$ for each cluster. From this comparison, we find that the root-mean-square deviation of the theoretical models from the observations is 0.16 mag, with no systematic variation in the residuals as a function of age or metallicity. This deviation is slightly larger than the mean error in the $M_K(RC)$ values of the 16 clusters, which we find to be 0.13 mag. Given that the mean deviation of the models from the observations is roughly consistent with the errors inherent in the latter, it is reasonable to conclude that the models are generally consistent with the observational data.

Figure 7 shows the Girardi models plotted along with the Alves (2000) field red clump star data. The models reinforce the conclusion drawn by Alves (2000) that M_K is insensitive to metallicity for nearby stars in this abundance range. Furthermore, given that a typical M_K error in Alves (2000) data is 0.11 mag, this figure suggests that the vertical spread in the M_K values is mainly the result of age effects among the field stars. Both the $10^{8.8}$ and $10^{9.2-9.4}$ year isochrones agree with the majority of the data. However, given the expectation that stars in the Solar neighborhood are likely to be near Solar-age, most of the HIPPARCOS stars in Fig. 7 probably have Log ages between 9.2 and 9.6 (1.6 to 4.0 Gyr).

It is interesting to note that the ages of the solar neighborhood stars as predicted by the models show a lack of stars around 10^9 years (Fig. 7). In contrast, using a model of the solar neighborhood RC that assumes a constant star formation rate, Girardi & Salaris (2001) expect an age distribution for the RC stars that peaks at 1 Gyr with approximately 60% of the stars having this age. The discrepancy in this result with the apparent ages of the HIPPARCOS RC stars likely indicates a non-constant star formation rate in the solar neighborhood; this is not surprising if the formation of stars is triggered by density waves traveling through the solar neighborhood, which is an intrinsically episodic process.

4. Application As a Distance Indicator

An important aspect of this study is the application of the K-band red clump absolute magnitude as a distance indicator. To optimize this application in the present work, we seek a range of age and abundance over which variations in $M_K(RC)$ are minimized. Inspecting Fig. 4, we see that if the age of the stellar population is in the range $2 \lesssim$Age$\lesssim 6$ Gyr and the metal abundance is between $-0.5 \lesssim$[Fe/H]$\lesssim 0.0$, then the intrinsic variation in $M_K(RC)$ is minimized suggesting that uncertainties in our knowledge of these properties are inconsequential in the determination of the distance. Based on these considerations, we have selected the open cluster NGC 2158. This cluster possesses 2MASS photometry, and it is included in the study of Twarog et al. (1997), so we have a metallicity value ($[Fe/H] = -0.24 \pm 0.06$) which is on the same system as the other clusters in this study. The age shift described in section 2.1 is also applied to NGC 2158 giving us an age of 1.6 ± 0.2 Gyr. We note in passing that NGC 2158 was not included as part of our $M_K(RC)$ calibration because the distance given in Twarog et al. (1997) was determined using the magnitude of the RC and not main sequence fitting.

For the reddening toward NGC 2158 we can utilize the data in Table 1 to parameterize the intrinsic color of the red clump ($(J-K)_0$) in terms of the metal abundance and age. Figure 8 shows $(J-K)_0$ versus $[Fe/H]$ (left panel) and age (right panel) for the clusters in our sample. Using the interpolation discussed in section 3.3, we can determine the intrinsic color of NGC 2158 given its metallicity and age, for which we find $(J-K)_0 = 0.597 \pm 0.003$. We calculate the error in $(J-K)_0$ by determining the uncertainty resulting from σ_{age} and $\sigma_{[Fe/H]}$ and adding these in quadrature. Comparing the implied intrinsic color of the red clump with the apparent color, $(J-K) = 0.821 \pm 0.006$, we find $E(J-K) = 0.224 \pm 0.007$. Converting this to a color excess in the optical regime, we find $E(B-V) = 0.43 \pm 0.013$, which is in good agreement with published values (e.g. Christian et al. 1985; Twarog et al. 1997). The preceding method represents an internally consistent formalism which can be utilized to estimate the reddening of a cluster.

The interpolation on $M_K(RC)$ using only the open cluster data predicts $M_K = -1.64 \pm 0.08$ for NGC 2158. Along with $E(B-V) = 0.43$ and the apparent RC K-band magnitude, $K(RC) = 11.55 \pm 0.02$, we find $(m-M)_V = 14.38 \pm 0.09$. Our distance modulus for NGC 2158 agrees within the errors with the main sequence fitting modulus of $(m-M)_V = 14.4 \pm 0.2$ found by Christian et al. (1985), but is slightly lower than that determined by Twarog et al. (1997) of $(m-M)_V = 14.5$.

5. Conclusions

In this paper, we have sought to establish the K-band absolute magnitude of the helium burning red clump stars ($M_K(RC)$) as a distance indicator. To facilitate this, we have utilized infrared photometry from the 2MASS catalog along with distances, metallicities, and ages for 14 open clusters and 2 globular clusters. Our sample encompasses an age range from 0.63 Gyr to 12 Gyr and metallicities from –1.15 to 0.15 dex. Based on an analysis of these data, we draw the following conclusions.

1. There is a statistically significant range of $M_K(RC)$ values among the star clusters in our sample. In particular, for the 14 open clusters, we calculate $\langle M_K(RC) \rangle = -1.62$ with a standard deviation of 0.21 mag. In contrast, the mean error in these $M_K(RC)$ values is 0.13 mag.

2. Upon inspection of figures 5 and 6, we find that for clusters younger than $\sim$2 Gyr, $M_K(RC)$ is insensitive to metallicity but shows a dependence on age. In contrast, for clusters older than $\sim$2 Gyr, $M_K(RC)$ is influenced primarily by the metallicity of the population and shows little or no dependence on the age.

3. In general, $M_K(RC)$ is less sensitive to age and metallicity than $M_I(RC)$ over the parameter range common to both this paper and Sarajedini (1999) from which the $M_I(RC)$ values are taken.

4. Over comparable metallicity and age ranges, our average $M_K(RC)$ value of –1.62 mag is consistent with that of Alves (2000) which is based on solar-neighborhood red clump stars with HIPPARCOS parallaxes. We also suggest that the significant scatter in the Alves (2000) M_K data

is likely due to a range of ages between ∼1.6 and ∼4 Gyr among these stars.

5. The theoretical red clump models based on the formalism of Girardi et al. (2000) agree reasonably well with our observational data, indicating that age plays an important role in determining $M_K(RC)$ for younger populations while metallicity mainly affects older populations.

6. Using the K-band absolute magnitude of the red clump, we are able to compute the distance to the open cluster NGC 2158. Adopting an age of 1.6 ± 0.2 Gyr and $[Fe/H] = -0.24 \pm 0.06$, our calibration yields a distance of $(m - M)_V = 14.38 \pm 0.09$.

7. When determining distances for star clusters having $-0.5 \leq [Fe/H] \leq 0.0$ and $10^{9.2} \leq age \leq 10^{9.9}$, one can ignore the interpolation discussed in section 3.3 and simply use $< M_K(RC) > = -1.61 \pm 0.04$.

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REFERENCES

Alcaino, G. 1976, A&AS, 26, 359

Alves, D. 2000, ApJ, 539, 732

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., and Nasi, E. 1994, A&AS, 106, 275

Bessell, M. S. & Brett, J. M. 1988, PASP, 100, 1134 (BB)

Bolte, M. 1987, ApJ, 315, 469

Burki, G., & Meylan, G. 1986, A&A156 131

Cardelli, J. A., Clayton, G. C., and Mathis, J. S. 1989, ApJ, 345, 245

Carpenter, J. M. 2000, AJ, 120, 3139

Carpenter, J. M. 2001, AJ, 121, 2851

Carretta, E., and Gratton, R. G. 1997, A&AS, 121, 95

Christian, C. A., Heasley, J. N., and Janes, K. A. 1985, ApJ, 299, 683

Cole, A. A. 1998, ApJ, 500, L137

Crowl, H. H., Sarajedini, A., Piatti, A. E., Geisler, D., Bica, E., Clariá, J. J., and Santos, J. F. C. Jr. 2001, AJ, 122, 220

Girardi, L., Bressan, A., Bertelli, G., and Chiosi, C. 2000, A&AS, 141, 371

Girardi, L., and Salaris, M. 2001, MNRAS, 323, 109

Koornneef, J. 1983, A&AS, 51, 489

Paczyński, B., and Stanek, K. Z. 1998, ApJ, 494, L219

Sarajedini, A. 1999, AJ, 118, 2321 (S99)

Seidel, E., Demarque, P., & Weinberg, D. H. 1987, ApJS, 63, 917

Stanek, K. Z., and Garnavich, P. M. 1998, ApJ, 503, L131

Twarog, B. A., Ashman, K. M., and Anthony-Twarog, B. J. 1997, AJ, 114, 2556

Vandenberg, D. A. 2000, ApJS, 129, 315

Zinn, R., and West, M. J. 1984, ApJS, 55, 45

Zoccali, M., Renzini, A., Ortolani, S., Bragaglia, A., Bohlin, R., Carretta, E., Ferraro, F. R., Gilmozzi, R., Holberg, J. B., Marconi, G., Rich, R. M., and Wesemael, F. 2001, ApJ, 553, 733

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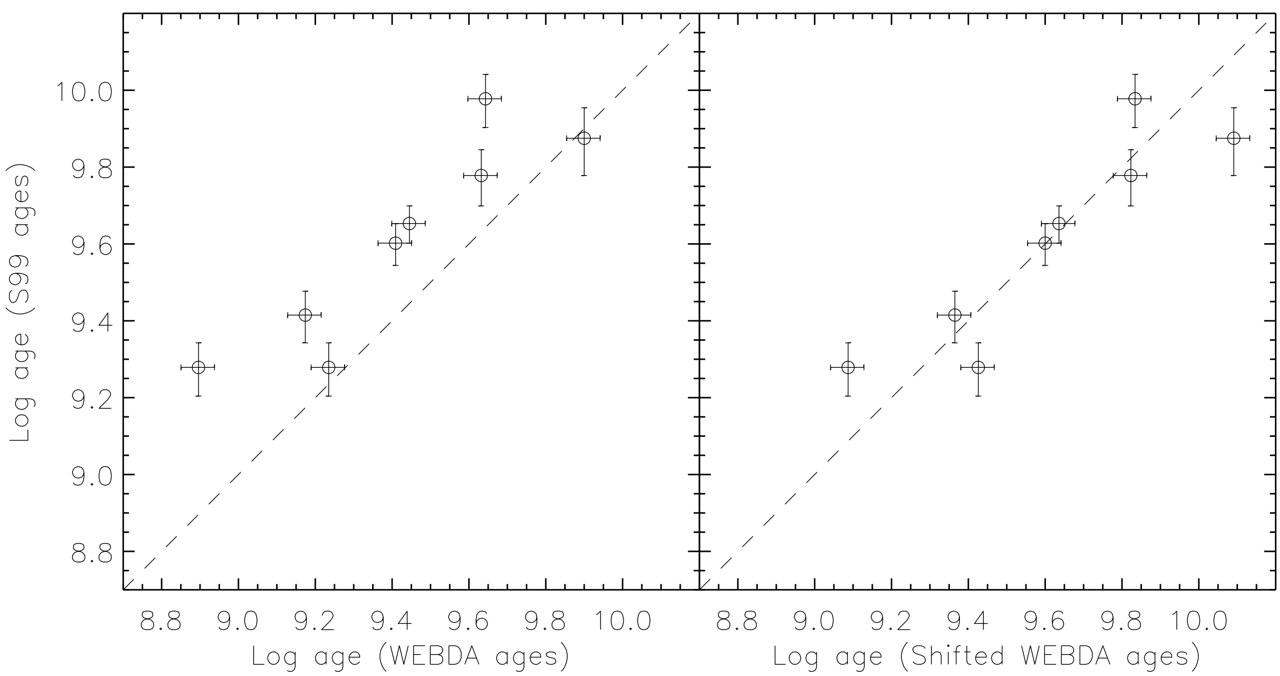
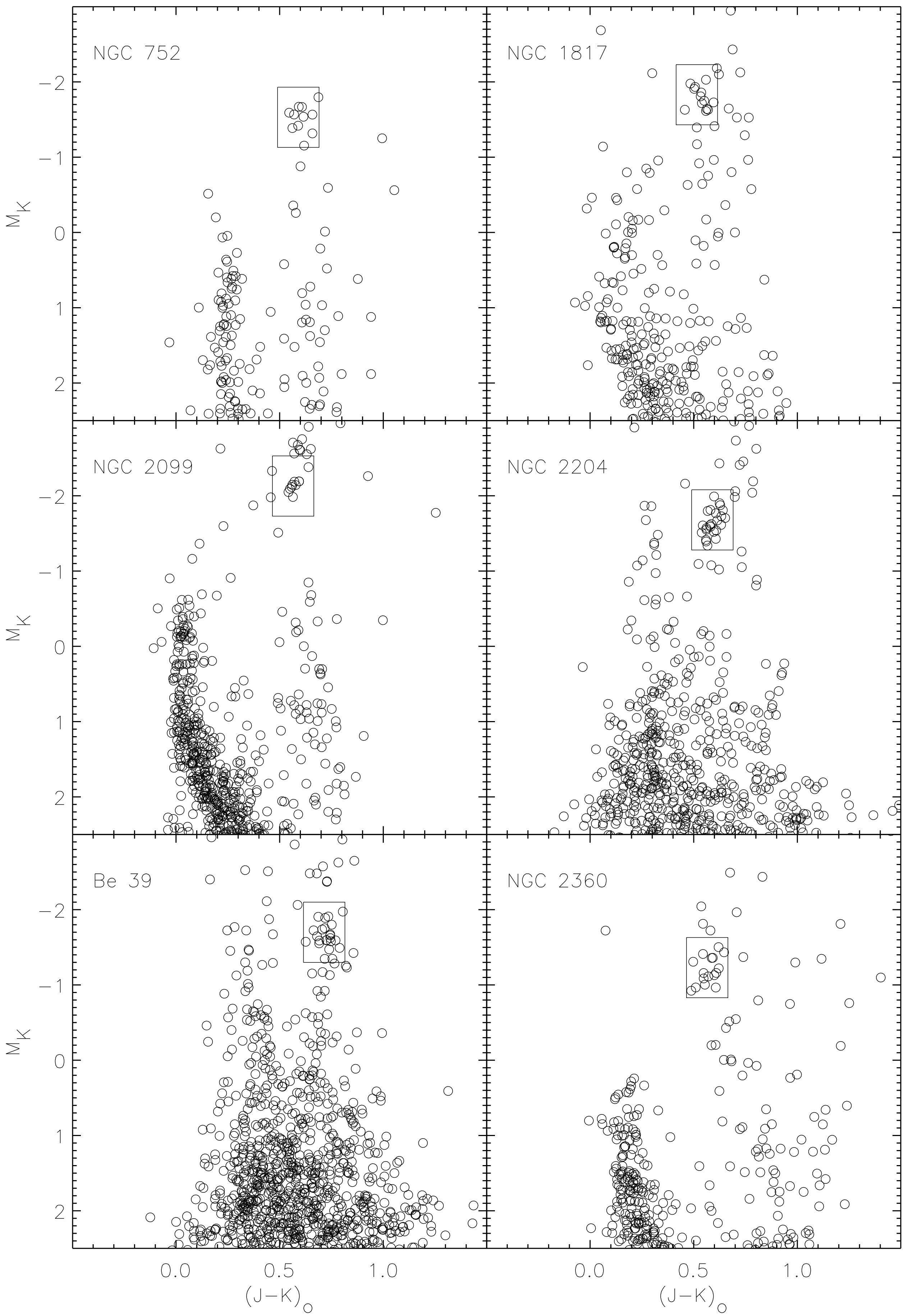


Fig. 1.— The left panel shows the ages from WEBDA plotted against those from S99. Due to the systematic difference between the systems, we shift the WEBDA ages older (right panel) by Δ $log(Age) = 0.191$ to place them on the same system as S99.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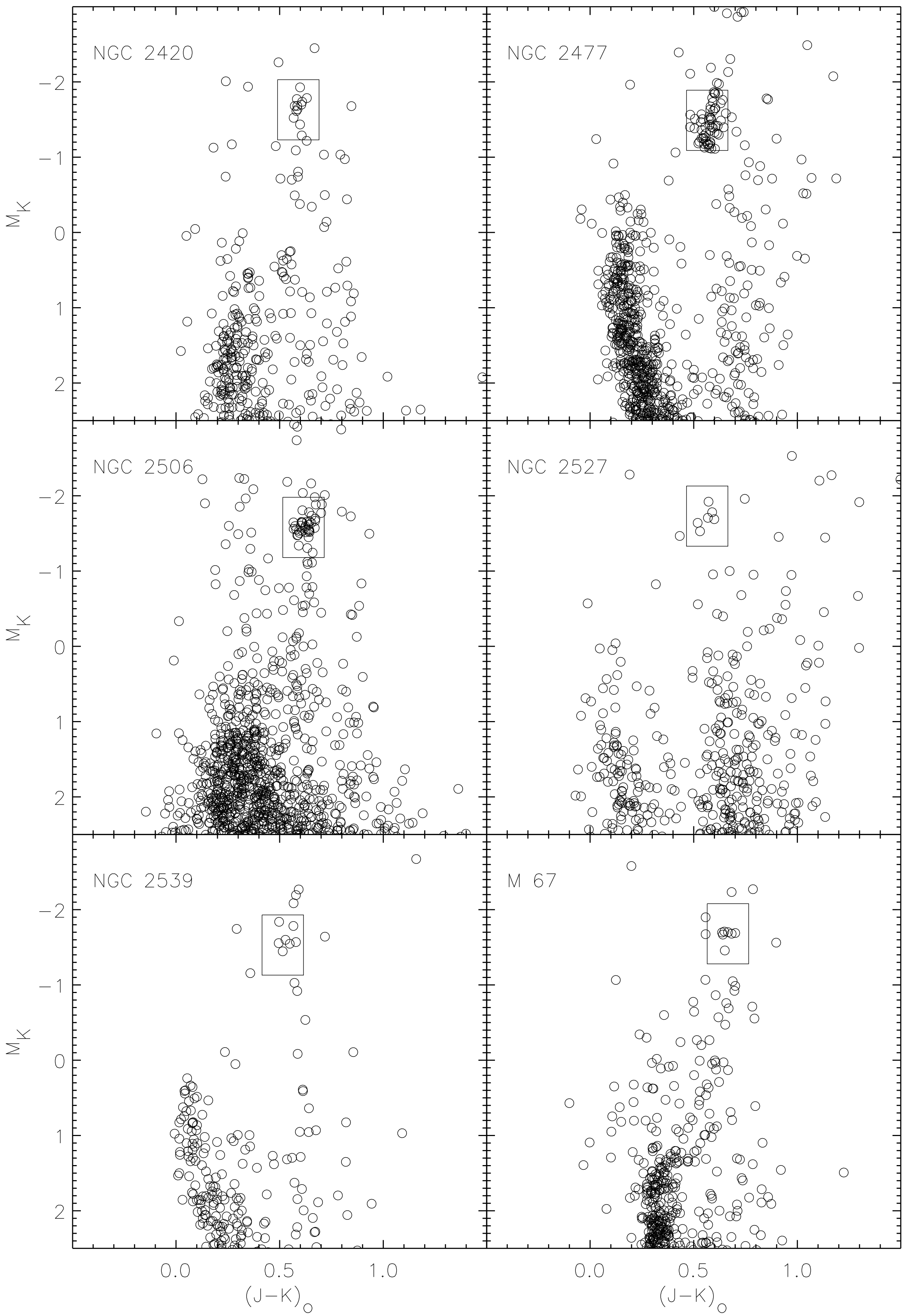
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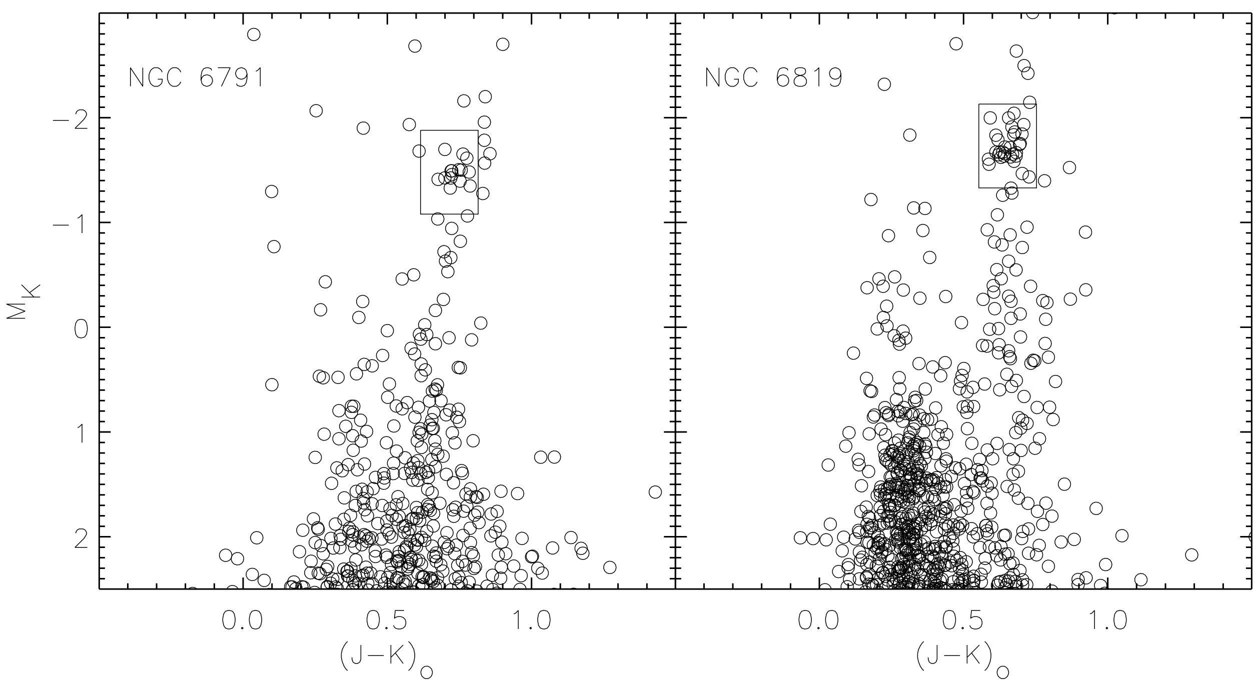

Fig. 2.— Infrared color-magnitude diagrams for the 14 open clusters in our sample with a box indicating the location of the red clump stars. All stars within the box are used in calculating the median K magnitude of the red clump.

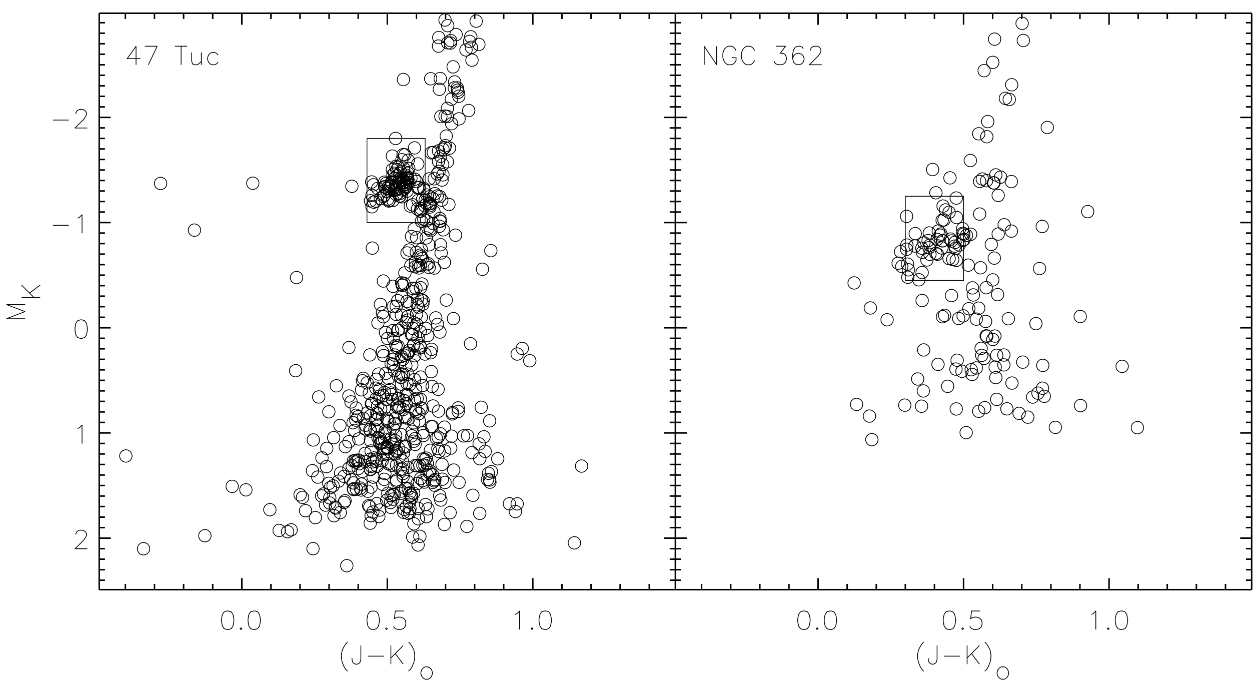

Fig. 3.— Same as Fig. 2., but for the globular clusters in our sample.

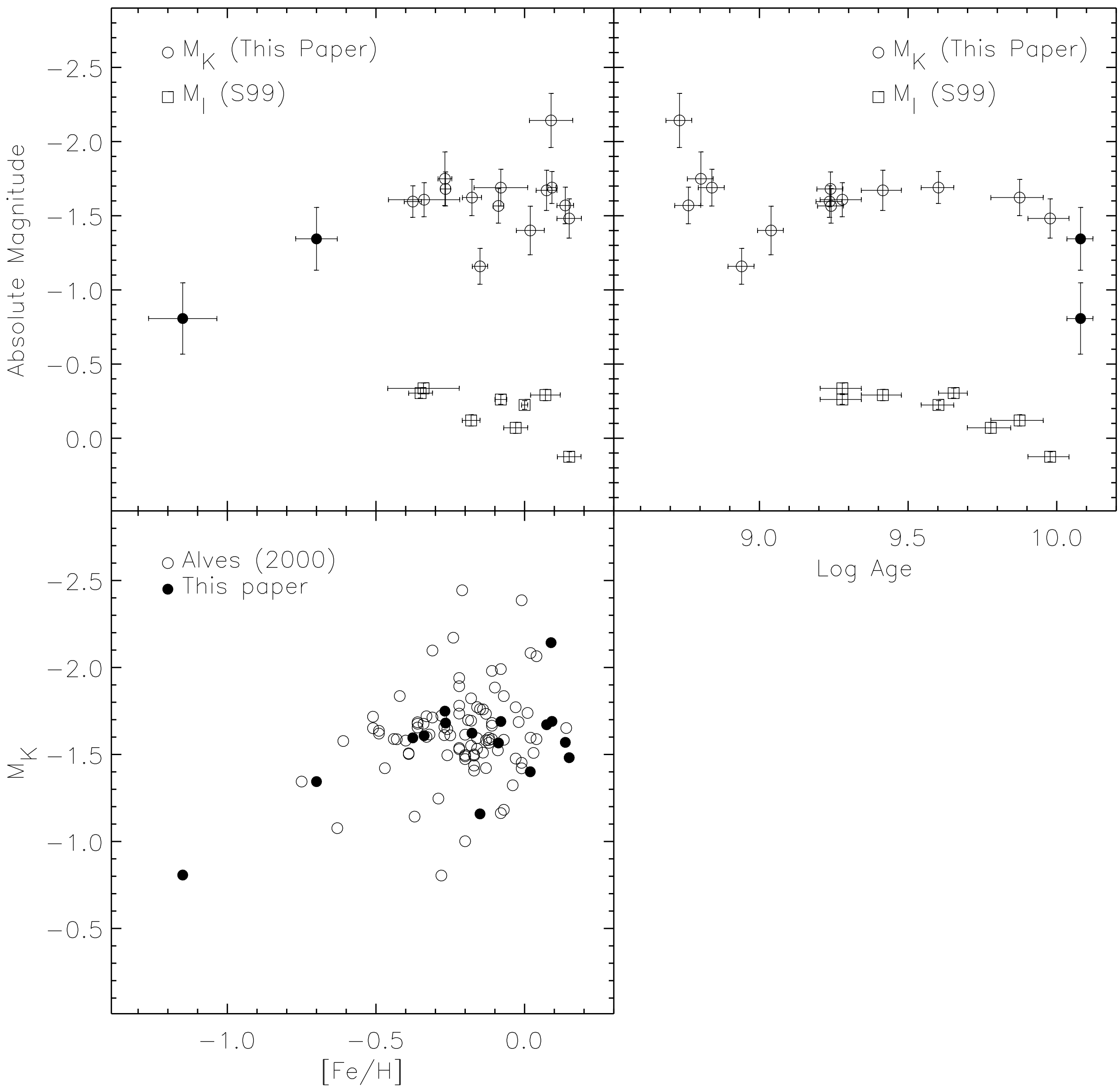

Fig. 4.— The upper panels show the variation of red clump absolute magnitude as a function of age (top left panel) and $[Fe/H]$ (top right panel). The open circles represent K-band absolute magnitudes ($M_K(RC)$) for the 14 open clusters while the filled circles signify $M_K(RC)$ values for the two globular clusters in the present sample. The open squares designate $M_I(RC)$ values from Sarajedini (1999). In the bottom panel, M_K for HIPPARCOS Solar neighborhood red clump stars from Alves (2000) (open circles) are compared with $M_K(RC)$ for clusters in the present paper (filled circles). These two data sets show remarkable agreement in their mean K-band magnitudes.

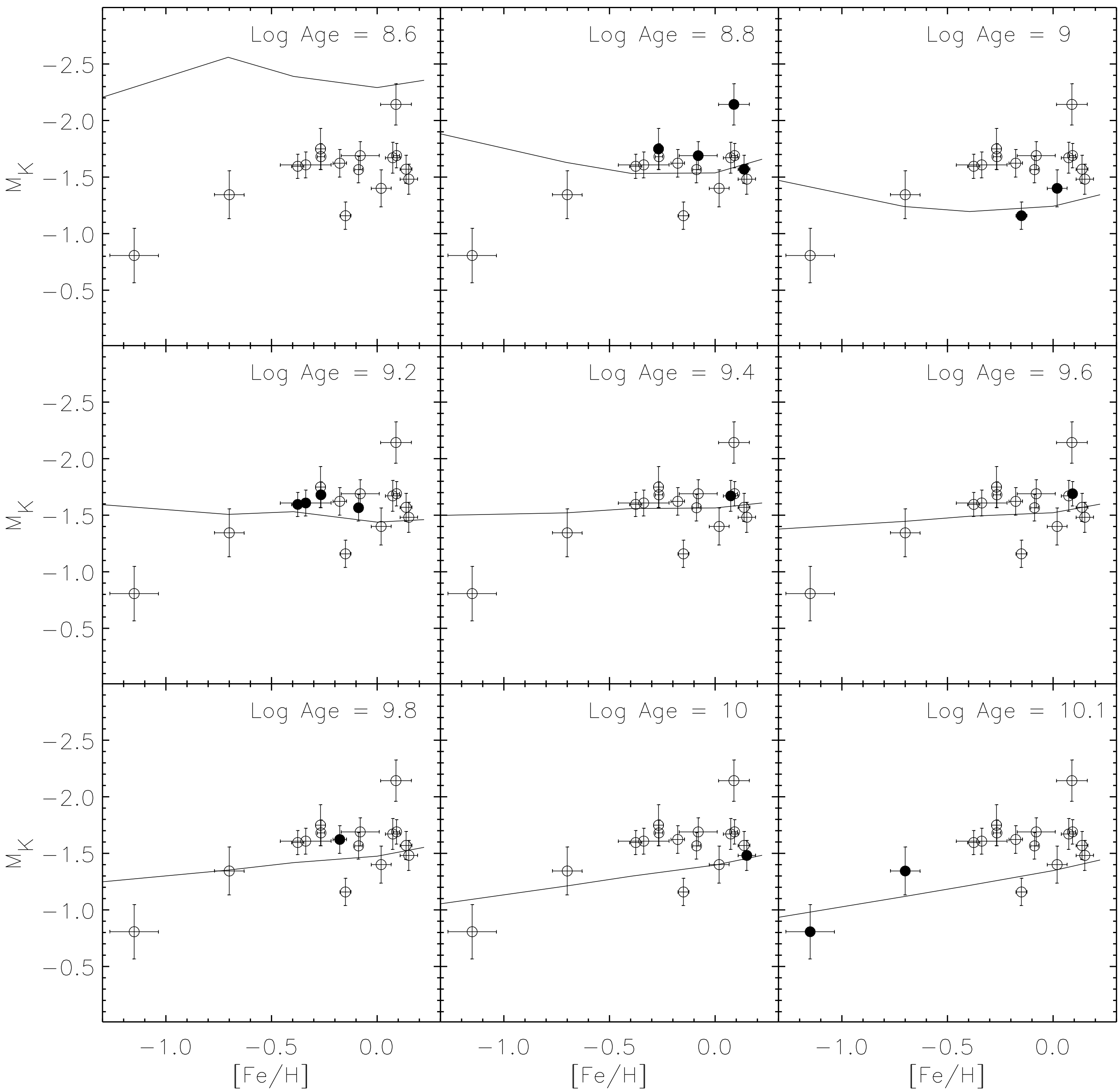

Fig. 5.— The observed variation of $M_K(RC)$ with the logarithm of the age as compared with the predictions of theoretical models (Girardi et al. 2000) for the indicated metallicities. The filled circles represent clusters with ages that are within ±0.1 dex of the model age in each panel. For the upper left and lower right panels, the filled circles represent clusters with $log(Age) \leq 8.7$ and $log(Age) \geq 10.05$, respectively. The remaining clusters in each panel are marked by open circles.

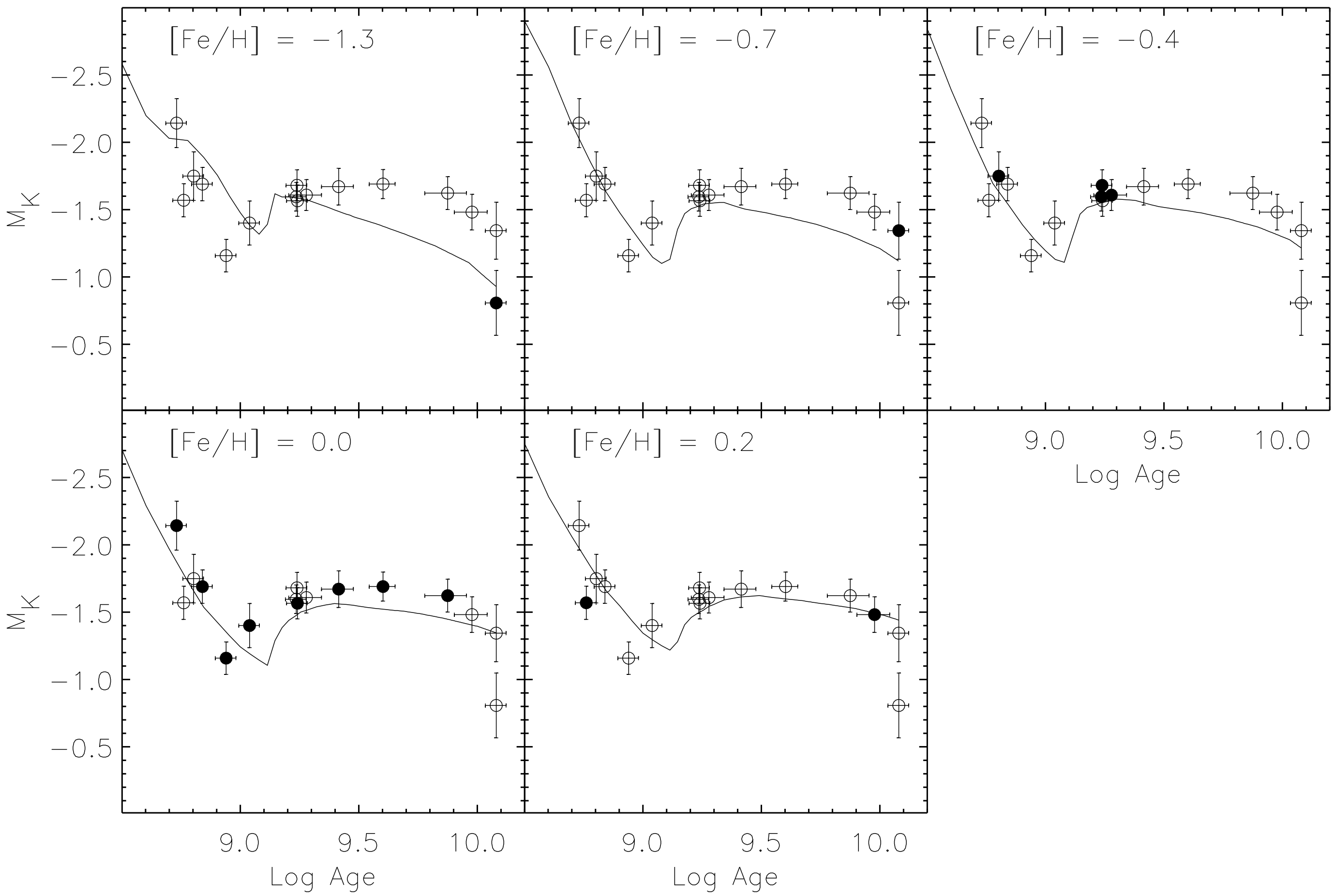

Fig. 6.— The observed variation of $M_K(RC)$ with metal abundance as compared with the predictions of theoretical models (Girardi et al. 2000) for specific ages. The filled circles denote the clusters with $[Fe/H]_{min} \leq [Fe/H] \leq [Fe/H]_{max}$, where $[Fe/H]_{min}$ and $[Fe/H]_{max}$ are halfway between the model shown and the next lower and next higher metallicity models, respectively. For the models of $[Fe/H] = -1.3$ and $[Fe/H] = 0.2$, clusters having $[Fe/H] \leq -1.0$ and $[Fe/H] \geq 0.1$, respectively, are marked with filled circles. The remaining clusters in each panel are shown by open circles.

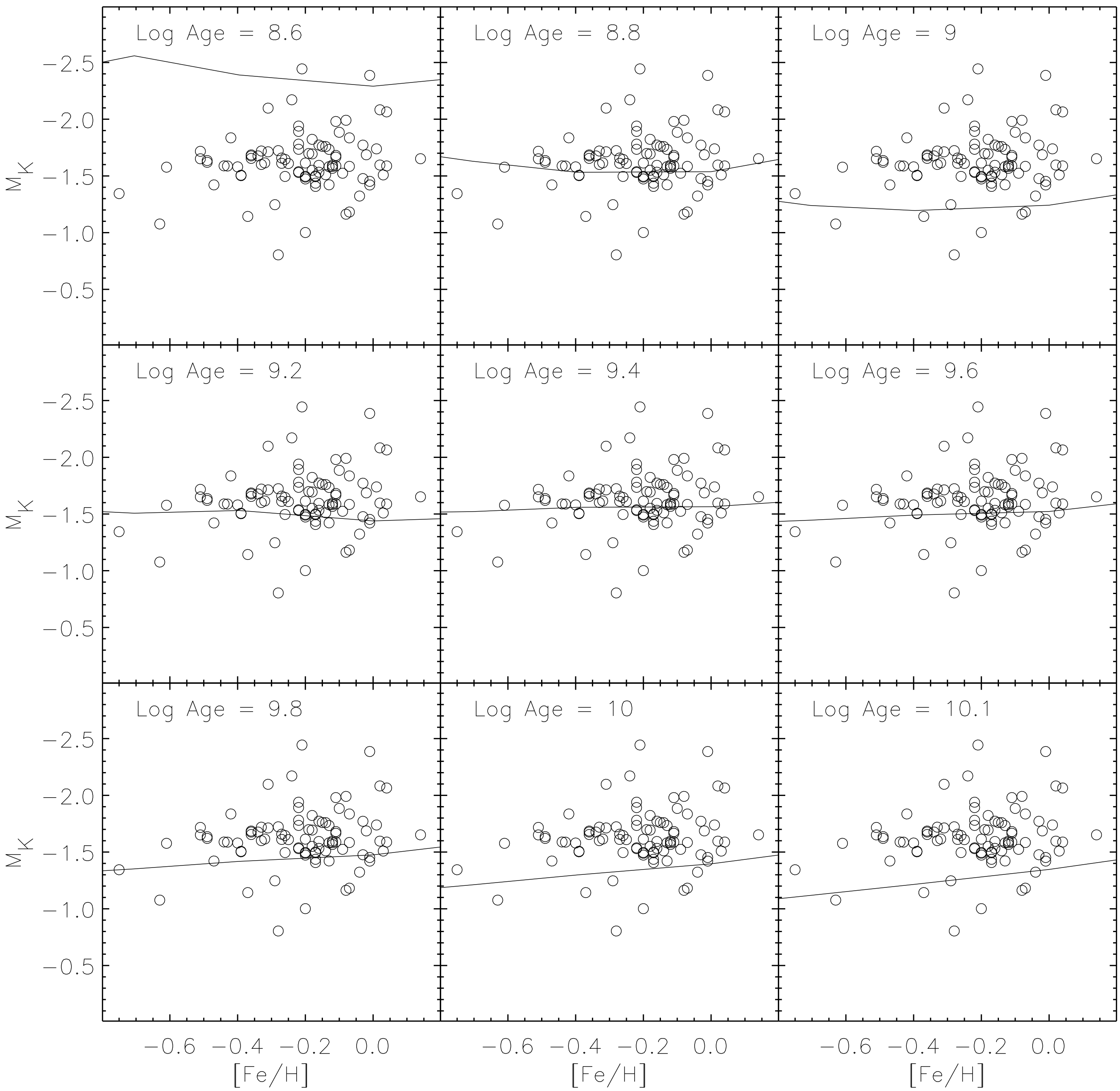

Fig. 7.— The K-band absolute magnitude of solar-neighborhood red clump stars with HIPPARCOS parallaxes versus their metallicities. The solid lines represent the predictions of theoretical models constructed by Girardi et al. (2000). The models suggest that the vertical spread in M_K can be explained by variations in the ages of the stars.

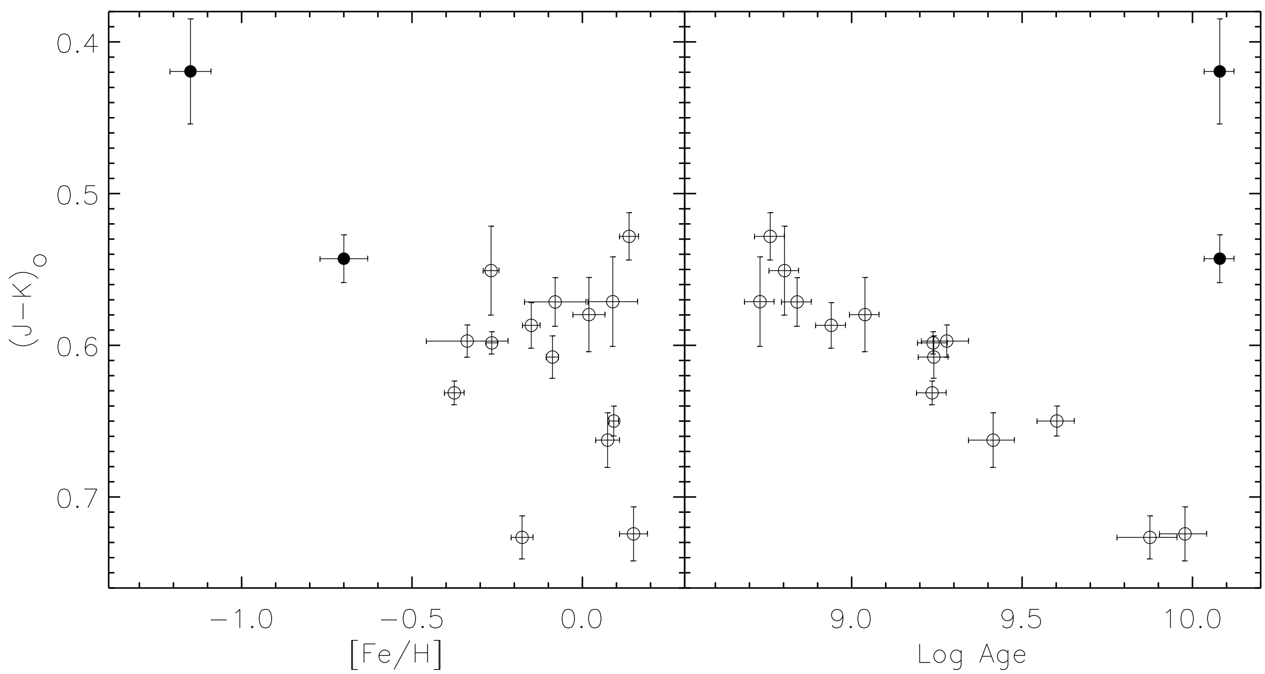

Fig. 8.— The left panel shows the intrinsic color of the RC plotted as a function of $[Fe/H]$ and the right panel shows it plotted as a function of age. The open circles represent the open clusters while the filled circles are the globulars.

Table 1. Open Cluster Information.

Name	Log Age	$(m-M)_V$ [a]	$E(B-V)$ [a]	$[Fe/H]$ [a]	$\sigma([Fe/H])$ [a]	M_K	$\sigma(M_K)$	$(J-K)_o$	$\sigma(J-K)_o$
NGC 752	9.24	8.35	0.04	−0.088	0.018	−1.566	0.116	0.608	0.014
NGC 1817	8.80	12.15	0.26	−0.268	0.023	−1.749	0.180	0.551	0.029
NGC 2099	8.73	11.55	0.27	0.089	0.073	−2.143	0.182	0.571	0.030
NGC 2204	9.28 [b]	13.30	0.08	−0.338	0.120	−1.608	0.115	0.597	0.011
Be 39	9.88 [b]	13.50	0.11	−0.177	0.032	−1.623	0.121	0.727	0.014
NGC 2360	8.94	10.35	0.09	−0.150	0.026	−1.159	0.121	0.587	0.015
NGC 2420	9.24	12.10	0.05	−0.266	0.017	−1.681	0.115	0.598	0.007
NGC 2477	9.04	11.55	0.23	0.019	0.047	−1.401	0.164	0.580	0.024
NGC 2506	9.24	12.60	0.05	−0.376	0.029	−1.596	0.106	0.631	0.008
NGC 2527	8.84	9.30	0.09	−0.080	0.090	−1.690	0.124	0.571	0.016
NGC 2539	8.76	10.75	0.09	0.137	0.028	−1.570	0.123	0.528	0.016
M 67	9.60 [b]	9.80	0.04	0.092	0.014	−1.690	0.108	0.650	0.010
NGC 6791	9.98 [b]	13.40	0.15	0.150	0.041	−1.482	0.132	0.724	0.018
NGC 6819	9.42 [b]	12.44 [b]	0.16 [b]	0.074	0.035	−1.671	0.136	0.663	0.018
47 Tuc	10.08	13.45 [c]	0.044 [c]	−0.70 [d]	0.07 [d]	−1.344	0.211	0.543	0.016
NGC 362	10.08	14.70 [c]	0.048 [c]	−1.15 [d]	0.06 [d]	−0.807	0.241	0.419	0.035

[a] From Twarog et al. (1997) unless otherwise noted

[b] From Sarajedini (1999)

[c] See section 2.2

[d] From Carretta and Gratton (1997)